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CAPTURE OF AN AXISYMMETRIC FREE JET IN A PIPE WITH  
APPLICATION TO POWER-AUGMENTED-RAM WING THEORY

by

Harvey R. Chaplin  
Earl F. McCabe, Jr.  
Harry A. Berman  
William J.H. Smithey

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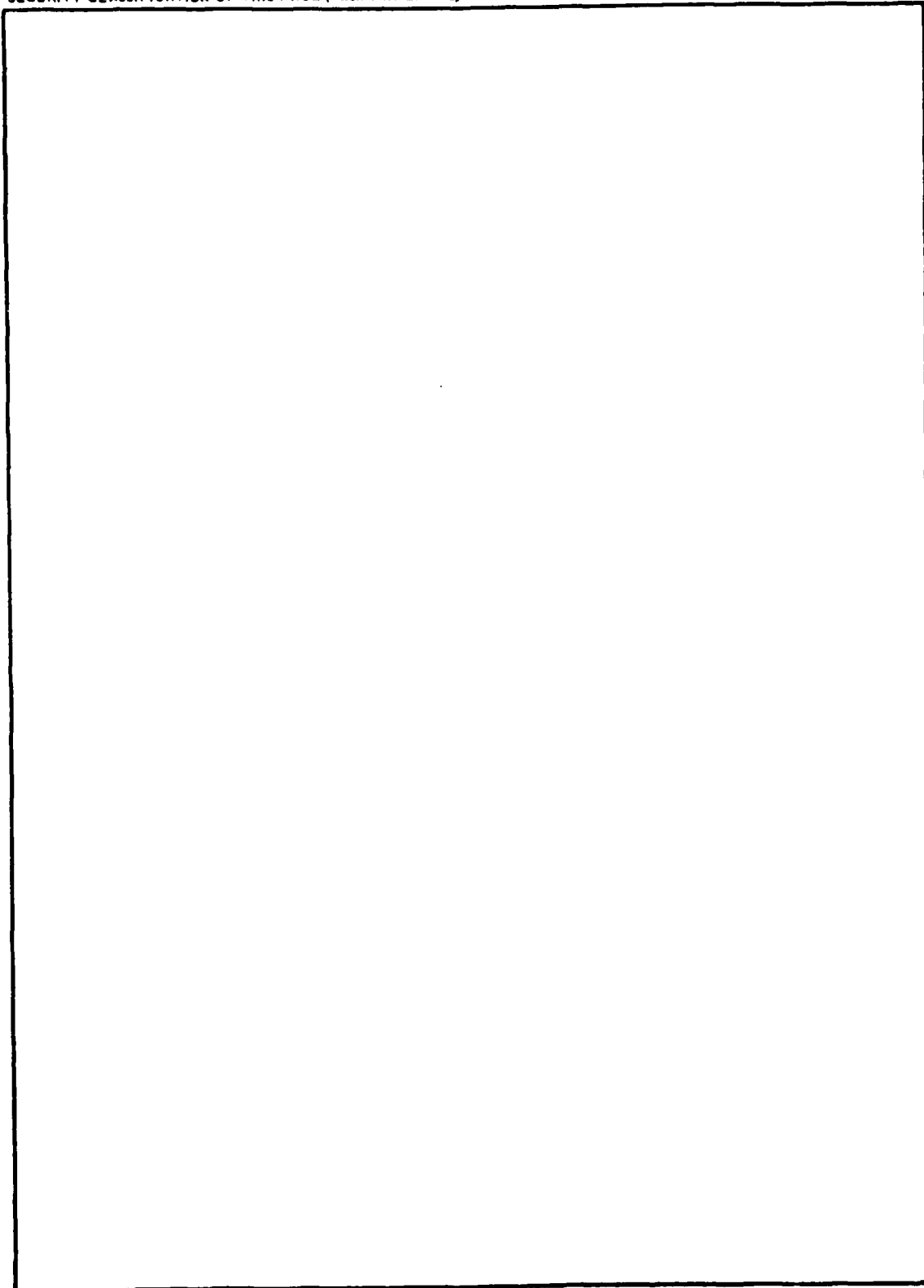
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## ABSTRACT

A theory of the two-dimensional power-augmented-ram wing with turbulent jets was previously validated over a range of experimental conditions which did not include very small ratios of jet nozzle area to capture area. In the present investigation a simple axisymmetric experiment was conducted to evaluate this condition. Results indicate that the original theory should provide useful predictions regardless of nozzle area ratio.

## ADMINISTRATIVE INFORMATION

This work was performed as part of the USMC Surface Mobility Program, Program Element 62543N, Task Area ZF 43-411-210, DTNSRDC Work Unit 1-1120-021.

## INTRODUCTION

A potential-flow theory<sup>1\*</sup> of the power-augmented-ram wing (PAR-Wing) indicates that best performance is obtained with jet nozzle area about half the capture area (product of wing span times wing height above the surface). However, experimental data indicate that performance does not deteriorate as rapidly with reduction of nozzle area ratio as potential theory would suggest, provided the jet nozzles are located sufficiently far forward of the wing to allow substantial turbulent mixing to take place. A theory<sup>2</sup> of the PAR-Wing with turbulent jets was developed which satisfactorily explained the existing data, including nozzle area ratios as low as about 0.2. Though less efficient from a fuel consumption viewpoint, PAR-Wing designs with small nozzle area ratios are of interest for short-endurance applications such as ship-to-shore craft, takeoff-and-landing systems and research craft (where considerable economies could be effected by using off-the-shelf engines rather than developing specially

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\*A complete listing of references is given on page 9.

tailored propulsors). Consequently, a simple experiment was devised with a ratio of jet nozzle area to capture area of about 0.046 as a check against any possible unexpected phenomena which might appear with very small nozzle area ratios.

#### EXPERIMENT

A 36-in. long pipe of 2.88-in. inside diameter and 3-in. outside diameter was instrumented with static pressure taps distributed along its length and equipped with interchangeable sharp-edged orifices at its downstream end. A nozzle of 0.62-in. inside diameter, zero convergence angle was directed coaxially into the upstream end of the pipe from various distances upstream. Nozzle thrust was estimated by measuring the mass flow and total temperature at a calibrated flowmeter in the supply line, assuming a standard turbulent pipe-flow velocity distribution at the exit, and solving iteratively for an average exit velocity and corresponding exit density which agreed with the measured mass flow. Nozzle dynamic pressure was varied between 0.23 psi and 0.74 psi, and the distance of the nozzle upstream of the pipe inlet was varied between 3.75 in. and 15 in.

#### THEORY

Theoretical pressure recovery in the pipe was calculated from the theory of Reference 2 (modified to account for the fact that the jet now has a classical axisymmetric velocity distribution<sup>3</sup> rather than the two-dimensional distribution assumed in Reference 2). The assumed axial velocity distribution in the free jet is

$$\frac{U}{U_{\max}} = \frac{1}{(1+\eta^2/4)^2} \quad (1)$$

where  $\eta = 15.174 r/x$  is the nondimensional distance from the jet axis,  $r$  is the distance in feet from the jet axis, and  $x$  is the distance downstream of the nozzle as indicated in Figure 1.

Using conservation of momentum,  $M$ , along the free jet

$$M = \rho U_{\max}^2 \int_0^{\infty} \left( \frac{U}{U_{\max}} \right)^2 2\pi r dr = M_o$$

and

$$M_o = \frac{\rho Q_o^2}{\pi D_o^2 / 4}$$

where  $Q_o$  is the volume flow at the nozzle exit, the relations

$$\frac{Q(\eta)}{Q_o} = 0.4566 \frac{x}{D_o} \left( 1 - \frac{1}{1+\eta^2/4} \right), \quad x > 2.19 D_o \quad (2)$$

and

$$\frac{M(\eta)}{M_o} = 1 - \frac{1}{(1+\eta^2/4)^3} \quad (3)$$

can be derived. Analogous to Reference 2, we now assume the pressure recovered in the pipe to be

$$P_c = \frac{1}{2} \rho \bar{U}_2^2 \left( 1 - C_c^2 D_2^4 / D_1^4 \right) \quad (4)$$

where  $C_c$  is the coefficient of contraction of the orifice flow and  $\bar{U}_2 = M_2/(\rho Q_2)$  is the average velocity of the contracted flow from the orifice, assumed to be the same as that part of the free jet contained within  $r \leq \frac{1}{2} \sqrt{C_c} D_2$  at distance  $x = \bar{x}$  downstream of the nozzle. ( $\bar{x}$  is the effective distance over which the jet continues to mix before being captured in the pipe; hence,  $\bar{x}$  can be taken approximately equal to  $X$ , the distance from the nozzle to the pipe, or  $X - D_1/3$  as a better estimate.) In other words, viscous and turbulent mixing effects which occur downstream of station  $\bar{x}$  are assumed negligible. Putting Equation (4) into nondimensional form yields

$$\frac{P_c \pi D_1^2 / 4}{M_o} = \frac{1}{2} \left( \frac{M_2}{M_o} \frac{Q_o}{Q_2} \right)^2 \frac{D_1^2}{D_o^2} \left( 1 - \frac{C_c^2 D_2^4}{D_1^4} \right) \quad (5)$$

The momentum and volume flow ratios are evaluated from Equations (2) and (3) using

$$\eta = 15.174 \sqrt{C_c} D_2 / (2\bar{x})$$

and making a short-hand substitution

$$\phi \equiv \frac{1}{1 + \eta^2 / 4} = \frac{1}{1 + 14.39 C_c D_2^2 / \bar{x}^2} \quad (6)$$

yields

$$\frac{P_c \pi D_1^2 / 4}{M_o} = 2.398 \frac{D_1^2}{\bar{x}^2} \left( \frac{1 - \phi^3}{1 - \phi} \right)^2 \left( 1 - \frac{C_c^2 D_2^4}{D_1^4} \right)$$

Observing that for a given  $D_1/\bar{x}$  this function is maximum when  $D_2 \rightarrow 0$  and  $\phi \rightarrow 1.0$ , the equation can be more conveniently written

$$\frac{P_c \pi D_1^{2/4}}{M_o} = \frac{a}{9} \left( \frac{1-\phi^3}{1-\phi} \right)^2 \left( 1 - \frac{C_c^2 D_2^4}{D_1^4} \right) \quad (7)$$

where

$$a = 21.58 D_1^2 / \bar{x}^2, \quad x \geq 3.285 D_1 \quad (8)$$

is the maximum value of the function.

Introducing the approximation

$$C_c \doteq 0.6 + 0.4 (D_2/D_1)^8 \quad (9)$$

yields, finally,

$$\frac{P_c \pi D_1^{2/4}}{M_o} = \frac{a}{9} \left( \frac{1-\phi^3}{1-\phi} \right)^2 \left( 1 - 0.36 \frac{D_2^4}{D_1^4} - 0.48 \frac{D_2^{12}}{D_1^{12}} - 0.16 \frac{D_2^{20}}{D_1^{20}} \right) \quad (10)$$

and substituting Equations (8) and (9) into Equation (6) gives more conveniently

$$\phi = \left( 1 + 0.4 a D_2^2 / D_1^2 + 0.267 a D_2^{10} / D_1^{10} \right)^{-1} \quad (11)$$

Equations (8), (10), and (11) now constitute a convenient set for calculation of the pressure recovery.

## RESULTS

Figure 2 presents a graph of theoretical pressure recovery versus  $(D_2/D_1)^2$  for various values of the parameter "a." Also plotted in Figure 2 are some sample experimental data for comparison. The experimental pressure recovery is taken to be the average of static pressure measurements taken in the vicinity of the 10-in. station of the 36-in. long pipe.

Figure 3 is a graph of theoretical maximum pressure recovery

$$\left( \frac{P_c \pi D_1^2 / 4}{M_o} \right)_{\max} = a = 21.58 D_1^2 / \bar{x}^2$$

Experimental data points are plotted at a value of "a" obtained by interpolation in Figure 2, and a value of  $21.58 D_1^2 / \bar{x}^2$  corresponding to  $\bar{x} = X - D_1/3$ , a somewhat arbitrarily chosen, but plausible, empirical relationship. The maximum achievable value of "a" appears to be about 1.4 as compared to about 1.1 achieved in earlier two-dimensional tests, and a maximum physically possible value of 2.0 (corresponding to the pipe acting as a perfect thrust reverser).

The value  $a = 1.4$  is first achieved when  $D_1/\bar{x} \doteq 0.254$ , i.e., when the nozzle is located about 4.2-pipe diameters ahead of the pipe, allowing about 3.9 diameters of free mixing length.

Figure 4 shows that, as the nozzle is moved closer to the pipe, the pipe does not fill immediately, and pressure recovery occurs progressively further and further downstream from the entrance. (Data presented are for a nozzle dynamic pressure of about 0.74 psi, the highest pressure tested. Data obtained at several lower nozzle pressures did not differ significantly from those presented.

There was a very slight trend toward lower nondimensional pressure recovery at lower nozzle pressures.)

#### CONCLUSION

The experimental data are in satisfactory agreement with the theory of Reference 2 (modified to account for a classical axisymmetric velocity distribution rather than a two-dimensional one). The maximum achievable value of nondimensional pressure recovery appears to be about 1.4, as compared to about 1.1 achieved in previous two-dimensional experiments, and 2.0 which would be achieved if the pipe were a perfect thrust reverser.

These results give every reason to believe that the theory of Reference 2 will be satisfactorily applicable to PAR-Wing performance estimates with no limit on the ratio of jet nozzle area to capture area.

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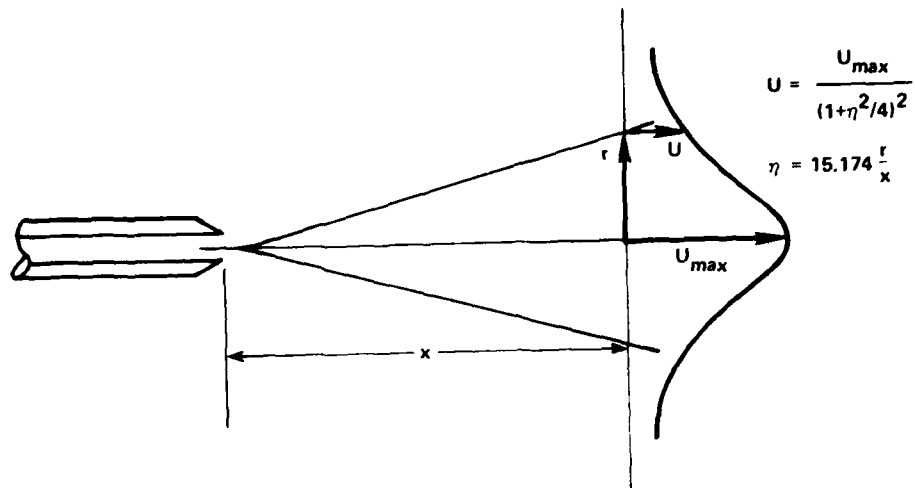


Figure 1a - Classical Velocity Distribution of an Axisymmetric Free Turbulent Jet  
(Reference 2)

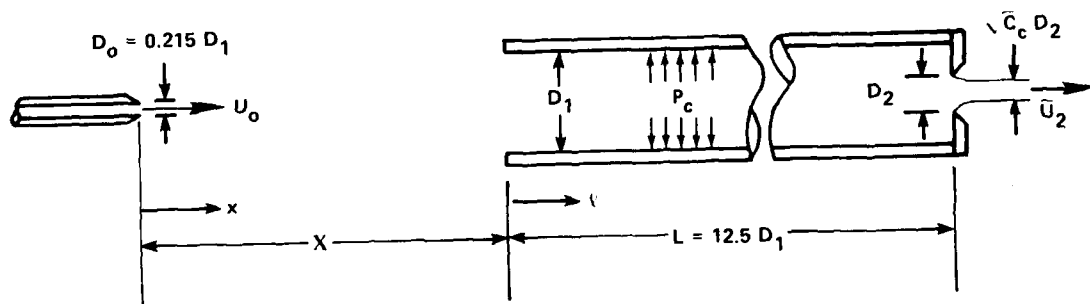


Figure 1b - Experimental Setup and Definitions

Figure 1 - Nomenclature

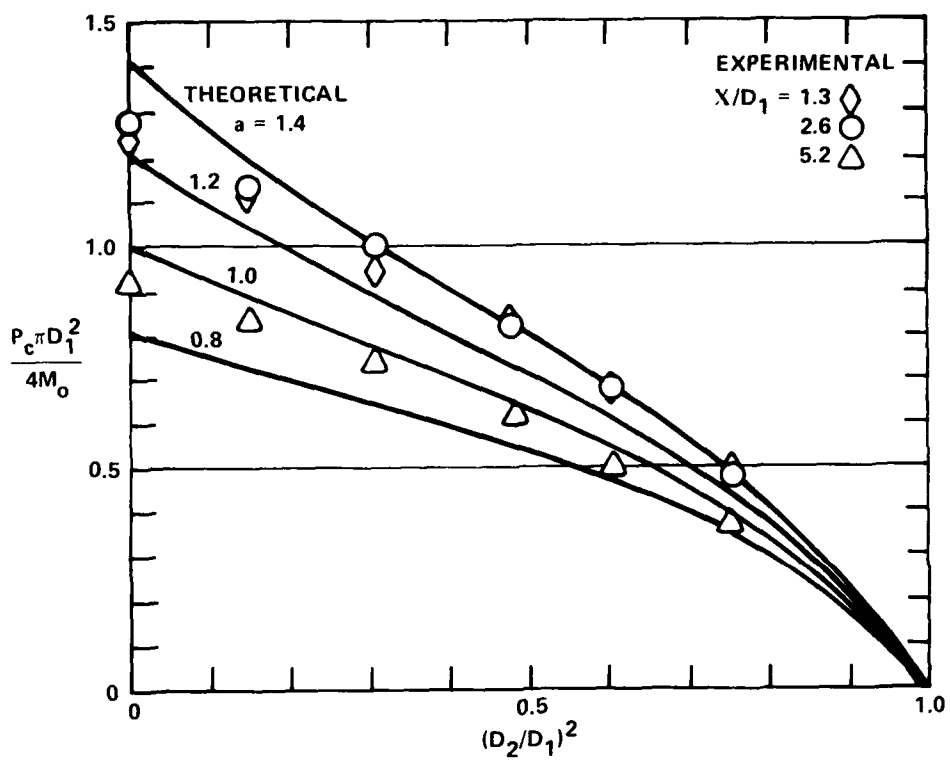


Figure 2 - Theoretical and Experimental Values of Pressure Recovery versus Orifice Area Ratio

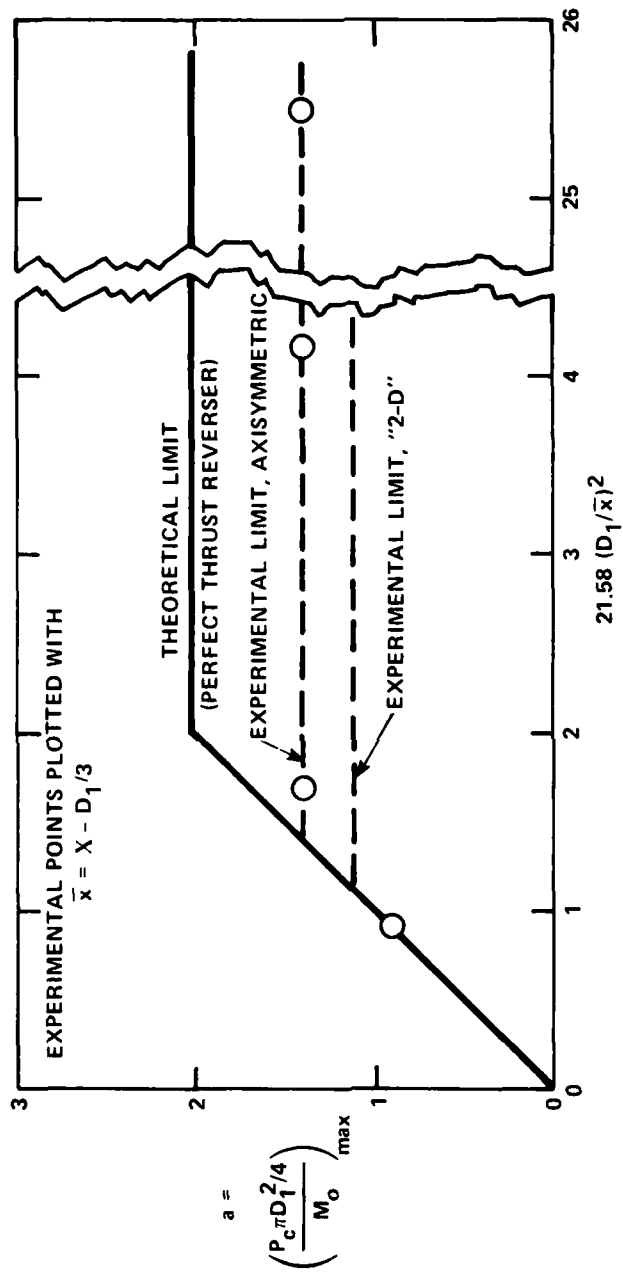


Figure 3 - Theoretical and Experimental Values of Maximum Pressure Recovery

Figure 4 - Pressure Distribution along the Pipe

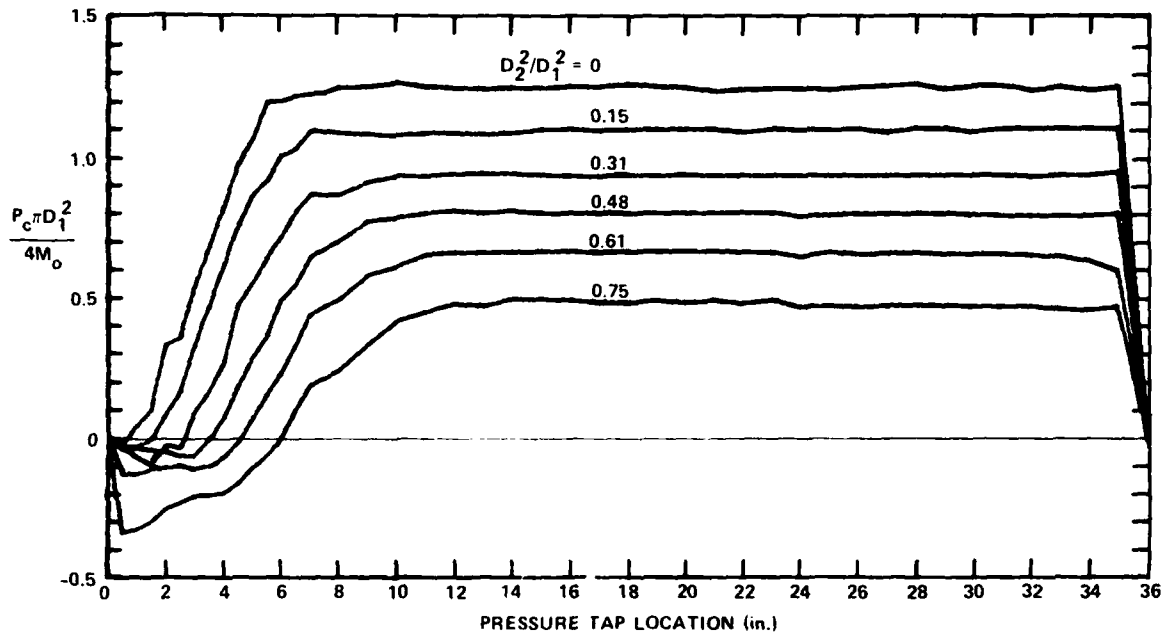


Figure 4a -  $X/D_1 = 1.3$

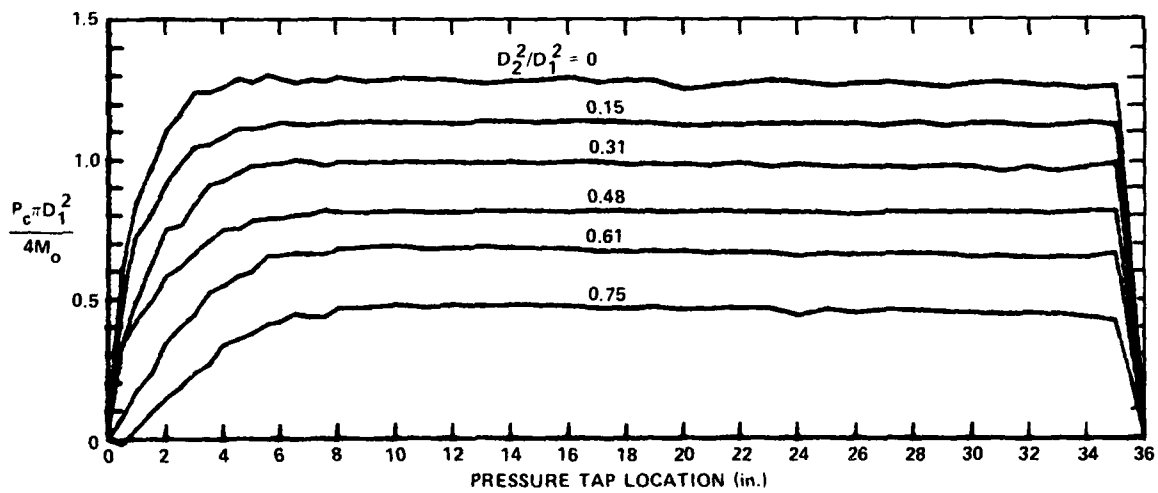


Figure 4b -  $X/D_1 = 2.6$

Figure 4 (Continued)

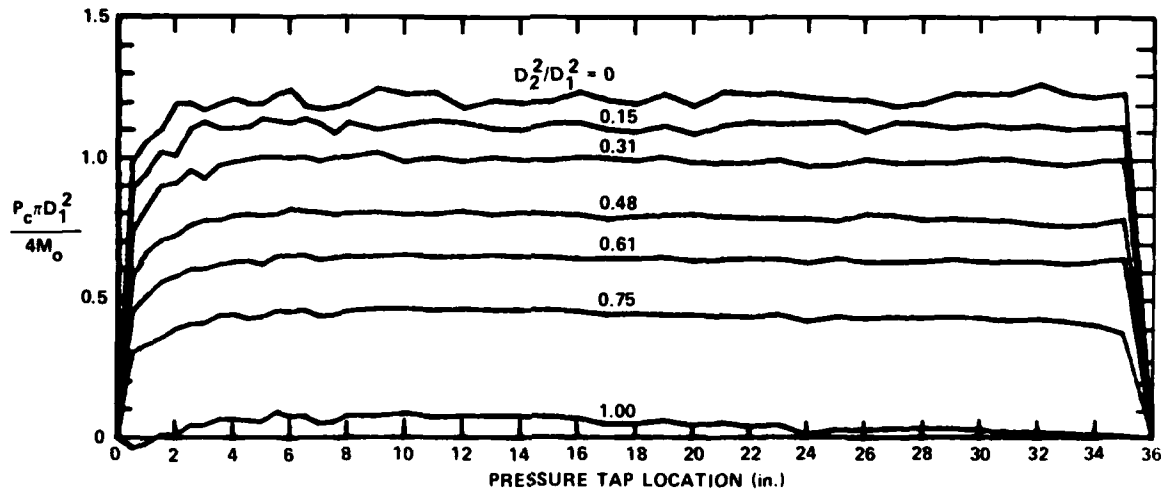


Figure 4c -  $X/D_1 = 3.9$

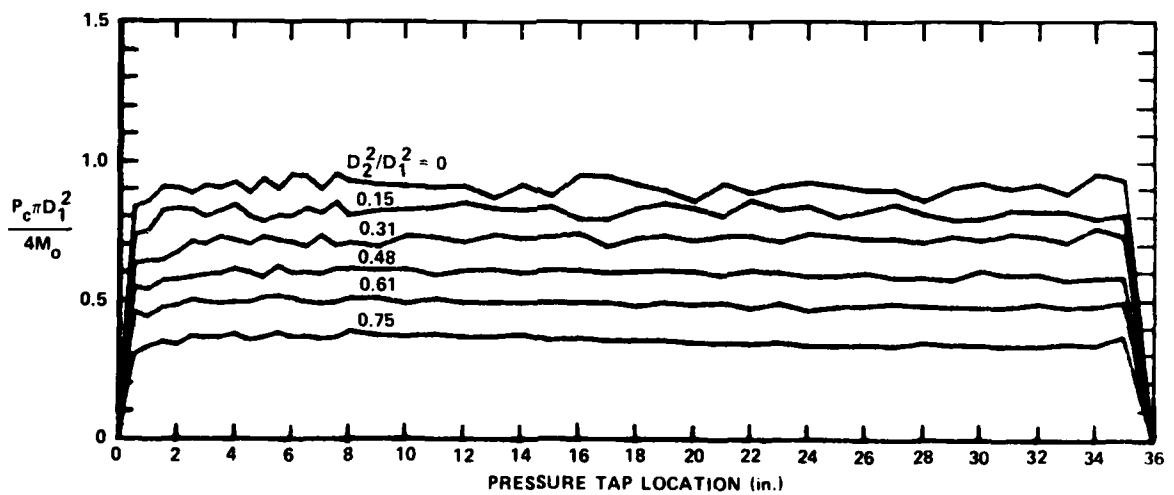


Figure 4d -  $X/D_1 = 5.2$

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